

On the Polyakov loop in 2+1 flavor QCD

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We study the temperature dependence of the renormalized Polyakov loop in 2+1 flavor QCD for temperatures $T < 210$ MeV. We extend previous calculations by the HotQCD collaboration using the highly improved staggered quark action and perform a continuum extrapolation of the renormalized Polyakov loop. We compare the lattice results with the prediction of non-interacting static-light hadron resonance gas, which describes the temperature dependence of the renormalized Polyakov loop up to $T < 140$ MeV but fails above that temperature. Furthermore, we discuss the temperature dependence of the light and strange quark condensates.

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I. INTRODUCTION

At high temperature strongly interacting matter undergoes a transition to a new state characterized by deconfinement and color screening (see e.g. Refs. [1, 2] for recent reviews). The Polyakov loop is an order parameter for deconfinement phase transition in $SU(N)$ gauge theories. After proper renormalization it is related to the free energy of a static quark F_Q [3, 4]. More precisely, it can be defined through the difference in the free energy of a system containing a static quark anti-quark ($Q\bar{Q}$) pair at infinite separation and a system without static charges at the same temperature $F_\infty(T)$, i.e. $L_{ren}(T) = \exp(-F_\infty(T)/2T) = \exp(-F_Q/T)$ [3]. In the confined phase $F_\infty = \infty$ since the static Q and \bar{Q} cannot be separated to infinite distance. Consequently, the Polyakov loop which transforms non-trivially under the center of the gauge group is zero. In the deconfined phase the static quark and anti-quark could be separated to infinite distance due to color screening which means breaking of the center symmetry $Z(N)$ [5, 6]. Dynamical quarks explicitly break the $Z(N)$ symmetry of the partition function and F_∞ is finite since the static Q and \bar{Q} can be now separated to infinite distance by creating a dynamical quark anti-quark pair from the vacuum, a phenomenon often called string breaking. In 2+1 flavor QCD with the quark masses realized in nature there is no phase transition related to deconfinement. Moreover, the renormalized Polyakov loop cannot be related to the singular part of the free energy density [7, 8]. However, the renormalized Polyakov loop is sensitive to the color screening in hot QCD medium, at high temperature it is closely related to the Debye screening mass (see e.g. [9]). In the opposite limit of very low temperatures F_Q is related to the binding energy of a static-light meson (see e.g. [10]). Thus the renormalized Polyakov loop is a good probe of the hot strongly interacting medium.

On the lattice with temporal extent N_τ the renormalized Polyakov loop is calculated according to the following formula

$$L_{ren}(T) = \exp(-cN_\tau/2) \left\langle \frac{1}{3} \text{Tr} \prod_{x_0=1}^{N_\tau} U_0(x_0, \vec{x}) \right\rangle, \quad (1)$$

where $U_0(x_0, \vec{x})$ is the gauge link variable in the time direction and c is the lattice spacing dependent normalization constant that ensures that the static potential calculated on the lattice has a certain value at a chosen distance [11]. In the recent past the renormalized Polyakov loop has been calculated on the lattice in 2+1 flavor QCD with physical quark masses using improved staggered fermion formulation [7, 8, 11–14]. Furthermore, using the stout improved staggered action continuum results for the renormalized Polyakov loop have been presented [14]. The aim of this paper is to study the renormalized Polyakov loop in the low-temperature and transition regions and to perform an independent continuum extrapolation using the highly improved staggered quark (HISQ) action [15]. While the temperature dependence of the Polyakov loop in QCD at high temperatures is very similar to its temperature dependence in pure gauge theory, this is not the case for the low temperature and the transition regions. To understand at which temperature color screening effects set in, it is important to clarify to what extent the temperature dependence of the Polyakov loop can be understood in terms of hadrons. As mentioned above, at very low temperatures the dominant contribution to F_Q is given by the lowest static-light state. As the temperature increases, more massive states will contribute as well and also the interactions of static-light hadrons with the medium will become more important. For the description of the bulk thermodynamic quantities it turns out that interactions between hadrons can be taken into account by adding the contribution of hadronic resonances. It is reasonable to assume that the effects of interactions of static-light hadrons with the hadrons in the medium can be accounted for by adding excited (resonance) states. Therefore, we calculate the renormalized Polyakov loop in the approximation of non-interacting gas of static-light hadrons and hadronic resonances as has been suggested recently [16]. Contrary to Ref. [16] (see also [17, 18]), where the experimental spectrum of heavy-light(strange) hadrons was used together with different model considerations, our analysis is largely based on the lattice QCD calculations of the spectrum of static-light and static-strange hadrons [19, 20]. We also consider different quark model analyses of the heavy-light(strange) hadron spectrum, compare them with each other and the

available lattice calculations, and use them to estimate the contribution of higher lying excited states to L_{ren} .

The rest of the paper is organized as follows. In section II we present our numerical results for the renormalized Polyakov loop. In section III we discuss the spectrum of static-light hadrons and the calculation of the Polyakov loop using the hadron resonance gas approximation for static-light hadrons. In the course of our numerical investigations we also calculated some quantities which are sensitive to the chiral transition in 2+1 flavor QCD and the corresponding results are presented in section IV. Finally, section V contains our conclusions.

II. NUMERICAL RESULTS

The chiral and deconfining aspects of the QCD transition have been studied by the HotQCD collaboration using lattices with temporal extent $N_\tau = 6, 8$ and 12 and combination of the tree-level improved gauge action and HISQ action in the quark sector [8]. This combination of the gauge action and quark action was referred to as the HISQ/tree action in Ref. [8] but here we refer to it as the HISQ action for simplicity. For reliable continuum extrapolations we need at least three lattice spacings. Therefore we performed calculations using $40^3 \times 10$ lattices, using as in the earlier work the rational hybrid Monte-Carlo algorithm [21]. The algorithmic details of dynamical HISQ simulations can be found in Ref. [22]. As in Ref. [8] calculations are performed for the physical value of the strange quark mass m_s and light quark masses $m_l = m_s/20$. This light quark mass corresponds to the pion mass of 160 MeV in the continuum limit [8], which is slightly above the physical value. However, for the Polyakov loop this small difference from the physical value plays no role. The parameters of the lattice simulations including the lattice gauge coupling $\beta = 10/g^2$ and the strange quark mass in lattice units are shown in Table I along with the corresponding temperatures. The last column of the table shows the accumulated statistics for each β value in terms of molecular dynamics time units. The lattice spacing a is determined from the r_1 parameter defined in terms of the zero-temperature static potential as

$$r^2 \frac{dV}{dr} \Big|_{r=r_1} = 1.0, \quad (2)$$

and we use the value $r_1 = 0.3106$ fm [23]. We use the parametrization of the lattice spacing and the quark masses as functions of the gauge coupling β along the lines of constant physics that are given in Ref. [8]. The β dependent normalization constant c that enters Eq. (1) was also taken from Ref. [8]. Since we are interested in the low-temperature behavior of the Polyakov loop, we also performed additional calculations on $32^3 \times 8$ lattices at $\beta = 6.125$, $am_s = 0.0966$ and $\beta = 6.175$ and $am_s = 0.0906$. These correspond to a temperature of 125 MeV and 131 MeV respectively. We accumulated 3180

β	m_s	T [MeV]	#TU
6.341	0.0740	123	7289
6.390	0.0694	129	4540
6.460	0.0642	138	4200
6.515	0.0604	146	4918
6.550	0.0582	151	4390
6.575	0.0564	155	3910
6.608	0.0542	160	4290
6.664	0.0514	168	5000
6.700	0.0496	174	4990
6.740	0.0476	181	4990
6.770	0.0460	186	4990
6.800	0.0448	192	5310
6.840	0.0430	199	4990
6.880	0.0412	207	4990

TABLE I: Run parameters for $40^3 \times 10$ lattices. The last column shows the accumulated statistics in terms of molecular dynamics trajectories.

molecular dynamics time units for $\beta = 6.125$ and 3732 time units for $\beta = 6.175$. The numerical results for the Polyakov loop are shown in Fig. 1. To obtain continuum results for the renormalized Polyakov loop we first perform a smooth spline interpolation of the numerical data for each N_τ . The errors of the spline interpolation are determined using the bootstrap method. Then we perform a $1/N_\tau^2$ continuum extrapolations at selected temperature values. This is motivated by the fact that the leading discretization errors in the staggered fermion formulation are proportional to a^2 , and therefore for the renormalized Polyakov loop they should scale like $(aT)^2 = 1/N_\tau^2$. For $T > 133$ MeV we have results for L_{ren} at 3 or 4 lattice spacings. Therefore for $135 \text{ MeV} \leq T \leq 210 \text{ MeV}$ it is straightforward to perform a continuum extrapolation at selected temperature values separated by 5 MeV. For temperatures below 133 MeV we have only few lattice data points for $N_\tau = 8$ and 10. Therefore in order to perform a continuum extrapolation we assumed that the coefficient in front of $1/N_\tau^2$ is temperature-independent and is the same as at $T = 135$ MeV. With these assumptions we get very good fits for a set of temperature values $123 \text{ MeV} \leq T < 132 \text{ MeV}$ separated by 3 MeV. We also performed linear fits with the coefficients in front of $1/N_\tau^2$ treated as free parameters, *i.e.* fits with zero degrees of freedom. These give values of the renormalized Polyakov loop that agree very well with the ones obtained from the previous procedure. The errors on the continuum extrapolated values of L_{ren} at these temperatures are taken to be equal to the largest error of the $N_\tau = 10$ results. Our continuum estimates for the renormalized Polyakov loop are also shown in Fig. 1 and compared with the continuum results obtained using the stout action [14]. The two lattice extrapolated continuum results agree with each other, except for $T = 140$ MeV, where our results are larger by two standard deviations.

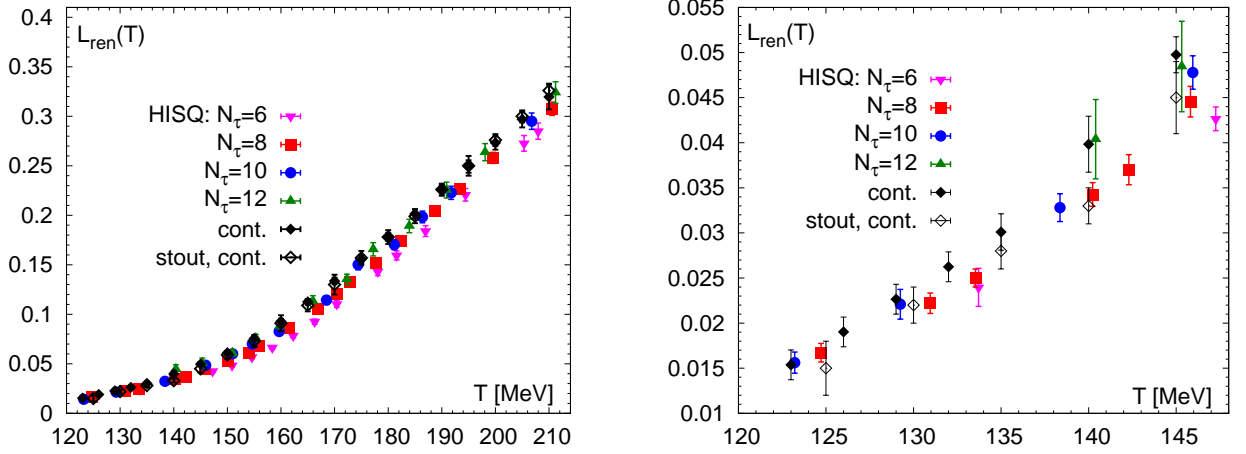


FIG. 1: The renormalized Polyakov loop calculated with the HISQ and stout action. The HISQ results for $N_\tau = 6, 8$ and 12 are from Ref. [8]. The continuum stout data are from Ref. [14]. The filled diamonds correspond to the continuum extrapolation for the HISQ action. The right panel shows the closeup of the Polyakov loop in the low-temperature region.

III. THE HADRON GAS MODEL

As discussed in section I, at very low temperature the free energy of a static quark is largely determined by the binding energy of the lowest static-light meson. In addition, there are contributions from static-strange mesons and baryons with one static quark. Thus, following Ref. [16], at very low temperature the Polyakov loop is given by the contribution of the lowest static-light states

$$3L_{ren} = 4 \exp(-M/T) + 2 \exp(-M_s^0/T) + \sum_I \sum_j (2I+1)(2j+1) \exp(-M_{I,j}^{B0}/T), \quad (3)$$

where the spin and iso-spin degeneracies of the meson states have been taken into account and the summation of all iso-spin (I) states as well as of all light and/or strange quark angular momentum states (j) for the lowest static-light baryons. Altogether we have contribution from 6 mesons and 21 baryons [16]. The factor 3 on the left hand side of the above equation originates from the color normalization in the definition of L_{ren} in Eq. (1) and can be seen from the spectral decomposition of the Polyakov loop correlator derived in [24]. Interactions with the medium are suppressed at very low temperatures but start to become more important as the temperature increases. One may try to include the interaction by assuming that it can be approximated by resonances. This assumption seems to work quite well for bulk thermodynamic quantities [14, 25–27]. The static-light meson contains a divergent self-energy contribution which needs to be subtracted. This leaves the mass of the ground static meson state undetermined, while the masses of all other states are given with respect to the mass of the lightest state $E_i = M_i - M_0$. Therefore we can generalize the above equation as follows

$$L_{ren} = \frac{1}{3} \exp(-\Delta/T) (4 + 2 \exp(-E_0^s/T) + \sum_{n,I,j} (2I+1)(2j+1) \exp(-E_{n,I,j}/T)). \quad (4)$$

Here E_0^s is the energy of the lightest static-strange meson with respect to the mass of the lowest static-light state M_0 . The first and the second terms correspond to the contribution of the ground state static-light and static-strange mesons, while the third term corresponds to the contribution of the baryon states and the excited meson states. The index n denotes different excited states corresponding to the same values of I and j . The renormalized Polyakov loop depends on the subtracted mass of the lowest static-light meson Δ . This needs to be adjusted to match the lattice data for the Polyakov loop at low temperatures, i.e. Δ should be adjusted to the specific scheme used for the normalization of the Polyakov loop on the lattice. This matching procedure will be discussed in subsection C. In the following two subsections we are going to discuss the meson and baryon contributions to L_{ren} separately.

A. Static mesons and their contribution to the renormalized Polyakov loop

Static-light and static-strange mesons are characterized by the angular momentum of the light (strange) quark and parity j^P . The spectrum of static-light mesons consist of approximately degenerate pairs with $j = |l \pm 1/2|$, where l is the orbital angular momentum. The spectrum of static-light(strange) mesons has been studied in 2-flavor lattice QCD by the ETMC collaboration for j up to $7/2$ that corresponds to orbital angular momentum $l = 0, 1, 2$ and 3 and is denoted by S, P_\pm, D_\pm, F_\pm [19]. Also the masses of first static-light and static-strange excited meson states for $1/2^-$ channel (first radial or S^* state in the ETMC notation) have been calculated [19]. To get rid of the divergent self-energy contribution the masses of different states are calculated with respect to the ground state (S state) mass both in

the light and the strange quark sectors. These mass differences have been extrapolated to the continuum limit and to the physical pion mass and are approximately the same for static-light and static-strange mesons, see Table 5 of Ref. [19]. The errors for the above mass difference vary between 12 MeV and 37 MeV. With all the spin and iso-spin degeneracies the number of states identified on the lattice is 96. To calculate the Polyakov loop according to Eq. (4) we need to know E_0^s , the energy (mass) of the lowest static-strange meson with respect to the lightest static-light meson. We use phenomenological considerations to do so. Consider the spin-averaged mass of the ground state charmed (bottom) mesons with strangeness $S = 0$ and $S = -1$

$$\overline{M}_D = \frac{3M(D^*) + M(D)}{4} = 1975 \text{ MeV}, \quad (5)$$

$$\overline{M}_B = \frac{3M(B^*) + M(B)}{4} = 5314 \text{ MeV}, \quad (6)$$

$$\overline{M}_{D_s} = \frac{3M(D_s^*) + M(D_s)}{4} = 2076 \text{ MeV}, \quad (7)$$

$$\overline{M}_{B_s} = \frac{3M(B_s^*) + M(B_s)}{4} = 5404 \text{ MeV}. \quad (8)$$

Here we used the values of the charm and bottom meson masses from Particle Data Group [28]. We get $\overline{M}_{D_s} - \overline{M}_D = 100 \text{ MeV}$ and $\overline{M}_{B_s} - \overline{M}_B = 90 \text{ MeV}$. Heavy quark effective theory predicts that the masses of heavy-light mesons and thus also the above difference should scale as the inverse of the heavy quark mass m_Q . Using this and the values of \overline{M}_D and \overline{M}_B as proxies for the charm and bottom quark respectively we get a value of 84 MeV for the difference of the lowest static-strange and static-light meson mass, i.e. $E_0^s = 84 \text{ MeV}$ for $m_Q = \infty$. It is interesting to mention that the value of the strange quark mass in \overline{MS} scheme $m_s(\mu = 2 \text{ GeV}) = 95(5) \text{ MeV}$ is close to the value of E_0^s . So E_0^s may be interpreted as a constituent strange quark mass.

To study the contribution of higher excited states we will use the D_s meson spectrum calculated on the lattice [29] as well as in a relativistic quark model [30–33]. The spectrum of D_s mesons has been calculated on the lattice using improved Wilson fermion actions [29]. One needs to establish a relation between the meson masses in the static case and the masses of D_s mesons. Heavy mesons, D_s mesons in particular, are characterized by nL_J with J being the total angular momentum of the meson, L being the orbital momentum and n being the radial quantum number. Obviously the $j = 0$ states in the static limit are identified with spin-averaged S -state D_s mesons. For finite heavy quark mass the $L - 1/2$ state in the static limit splits into two states L_{L-1} and L_L , while the $L + 1/2$ state splits into L_L and L_{L+1} state, e.g. P_- becomes $1P_0$ and $1P_1$, and P_+ becomes $1P_1$ and $1P_2$. The corresponding splittings, however, are small. Such a degeneracy pattern is indeed observed in the experimentally established positive parity (P -wave) D and D_s mesons. Furthermore, the mass difference of various D_s meson states calculated on the lattice and the spin-

averaged lowest S -state is in reasonable agreement with the mass difference in the static limit discussed above. Therefore it is justified to use the D_s meson masses calculated on the lattice as proxies for static-strange mesons. Since the above difference is approximately the same for strange and light quark cases we can use the same mass difference also for the light quarks. That allows to include the following excited states into the analysis: $2P$, $2D$ and $2F$. We identify the mass of $2L_-$ meson in the static case with the lowest $2L_L$ D_s meson mass and the $2L_+$ with the higher $2L_L$ D_s meson. With all the spin-iso-spin degeneracies this gives 90 states.

To include even higher excited states we use quark model predictions. The quark model can predict certain qualitative features of the heavy-light and static-light meson spectrum correctly [30–32]. However, the quark models also have problems. In the static limit the mass of the P_+ state is smaller than the mass of the P_- state just the opposite to what is observed on the lattice [19]. The mass of the P_+ in a quark model, calculated in Ref. [32], is 230 MeV below the lattice result. Similarly, the mass of the $2S$ state is 441 MeV below the lattice result [19]. Comparing the results of Ref. [30, 31] to Ref. [32] one may conclude that the model dependence is small for the $1P$ meson states, however, in the B_s sector the masses of the $2S$ states differ by about 300 MeV. We try to account for these problems by assigning a theoretical error to the masses of higher excited states.

We took the results of quark model calculations of D and D_s mesons [33] to estimate the contribution of $3S$, $4S$, $5S$, $3P$ and $1G$ states. From comparison of the results of different quark models as well as the comparison to the lattice results discussed above we estimate the uncertainty of the masses of the higher nS states ($n \geq 3$) to be 300 MeV, while for the other states we estimate it to be 150 MeV. It turns out, however, that contribution of these states to L_{ren} is negligible up to temperatures of 210 MeV for which the model makes sense. The excited states discussed so far should include all the possible states up to mass of 2 GeV above the ground state mass. It is unlikely that individual resonance states can be observed above that energy. In Fig. 2 we show the contribution of meson states to the renormalized Polyakov loop. We normalize the results by $L_0 = 4 \exp(-\Delta/T)/3$. The contribution of all static meson states calculated on the lattice in Ref. [19] is shown as the band, the dashed line includes the contribution of the higher excited states, while the thin solid line corresponds to the first static-strange meson only. The uncertainty band is determined by the errors of the static meson masses calculated on the lattice [19]. We see that at low temperatures the only meson state that has a significant contribution to L_{ren} in addition to the lowest state is the lightest static-strange meson, though the contribution of excited states cannot be completely neglected. Excited states (up to $1F$) become very important at higher temperatures, $T > 140 \text{ MeV}$. Finally, the contribution of higher excited states is quite small and is only visible for $T > 170 \text{ MeV}$.

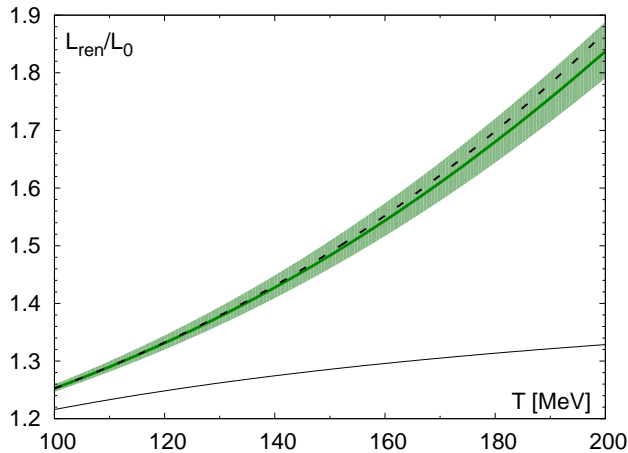


FIG. 2: Meson contribution to L_{ren} normalized by $L_0 = 4 \exp(-\Delta/T)/3$. The band shows the contribution of all static meson states calculated on the lattice (see text). The dashed line includes the contribution of higher excited states. The thin solid line corresponds to the contribution of the lightest static-strange meson only.

B. Baryon contribution to the renormalized Polyakov loop

The spectrum of baryons with one static quark has been studied by the ETMC collaboration [20] in 2 flavor QCD. The masses of static baryons with positive and negative parity and angular momentum of light quarks $j = 0$ and 1 have been calculated. These states correspond to the ground state and first orbital excitation of baryons with one heavy quark, i.e. to $1/2^+$, $3/2^+$ and $1/2^-$ and $3/2^-$. Counting the iso-spin and angular momentum degeneracies the lowest positive and negative parity baryons correspond to 79 states. The calculations have been carried out at one lattice spacing. The lack of continuum extrapolation is not of great concern, since based on the studies of the static meson spectrum, cutoff effects are expected to be small compared to the statistical errors. The results presented in Ref. [20] depend somewhat how the lattice spacing is set. More precisely, using f_π the lattice spacing was determined to be 0.079(3) fm, while using the nucleon mass the lattice spacing turned out to be 0.089(5) fm. In our analysis we use the values of the masses obtained by fixing the lattice spacing through the nucleon mass m_N since this procedure gives a value of the r_0 parameter that is consistent with other determinations [8, 13], namely $r_0 = 0.473 \pm 0.09(stat.) \pm 0.16(syst.)$ fm [34]. Setting the scale with f_π gives $r_0 = 0.42$ fm [35] which is much smaller than any other determination. The lowest lying positive and negative parity baryons give a fairly large contribution to the renormalized Polyakov loop, in fact, the largest contribution next to the ground state mesons. However, it turns out that higher excited states cannot be neglected. We can use quark models to estimate the

contribution of higher lying baryon states to L_{ren} .

The spectrum of baryons containing one heavy (c or b) quark has been studied in relativistic quark model [36] and in relativistic quark-diquark model [37]. The analysis of Ref. [36], however, was restricted to $\Lambda_{b,c}$ and $\Sigma_{b,c}$ baryons. We will use the spectrum of excited heavy baryons containing b quark as a proxy for the spectrum of higher excited baryon states with a static quark. The masses of baryons with a static quark are determined by the angular momentum of the light quarks j . Therefore the heavy baryons form doublets with almost the same mass that correspond to the same angular momentum j of the light quarks and total angular momentum $J = j \pm 1/2$. In our analysis we consider the mass difference of the baryon with the lower angular momentum in the doublet and the spin averaged mass of $B(B^*)$ mesons. These mass differences obtained in a quark model are compared to the static baryon spectrum for the lowest positive and negative parity states calculated on the lattice. It turns out that the agreement between the lattice results and the model calculations is quite good if the nucleon mass is used to set the lattice spacing. In fact, the lattice results agree with the model calculations within the errors. For the Λ_b and Σ_b family we also find good agreement between the diquark model and Ref. [36] for the lowest states of both parity. In our calculations we use the spectrum calculated in Ref. [37] which corresponds to baryon states with angular momentum up to $J = 11/2$ equivalently to $j = 5$ of the light quarks and up to 5 radial excitations. Counting all the spin and iso-spin degeneracies these correspond to 984 states.

As discussed above, different model calculations agree with each other for the lowest positive and negative parity states. Unfortunately, the agreement is not that good for the higher excited states. To estimate the sensitivity of the Polyakov loop to the model uncertainty of the higher excited baryon states we calculated the contribution of excited Λ_Q and Σ_Q baryons to L_{ren} including all states up to $J = 7/2$ using the results of Ref. [36] and of the diquark model [37]. The contributions of Λ_b to L_{ren} is a factor of two larger if one uses the spectrum from Ref. [36] compared to the case where the Λ_b spectrum from the diquark model is used. On the other hand, the contribution of the Σ_b baryons is factor of two smaller if one uses the results of Ref. [36] instead of the results of the diquark model. Therefore we estimate that contribution of the higher excited baryon states is uncertain by factor 2.5. This is the largest source of uncertainty in the hadron resonance gas model for $T > 170$ MeV. The contribution of baryons to the renormalized Polyakov loop is shown in Fig. 3. The contribution of the static baryons identified on the lattice in Ref. [20] is shown as the solid line and the band. The error band corresponds to the uncertainty that has been evaluated using the errors on the static baryon masses. The contribution of all baryon states to L_{ren} is shown as the dashed black line. At temperatures $T < 120$ MeV the contribution of the baryons is below 10%. It becomes significant above that temper-

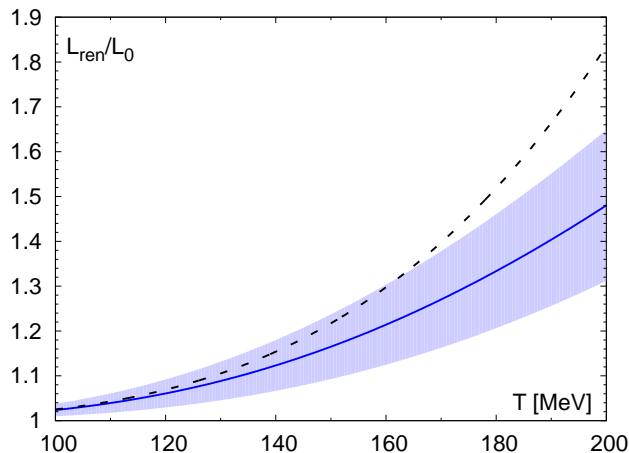


FIG. 3: The contribution of baryons to L_{ren} normalized by $L_0 = 4 \exp(-\Delta/T)/3$. The solid line and the band correspond to the contribution of the lowest positive and negative parity baryons, while the dashed line corresponds to the contribution of all baryon states.

ature. The contribution of higher excited states becomes significant only for $T > 140$ MeV. Therefore, as it will become clear in the next subsection, the uncertainty in the comparison to the lattice data due to the excited states is small.

C. Comparison with lattice results

Let us compare the hadron resonance gas model results with the lattice data discussed in section II. The comparison is easiest in terms of the free energy of an isolated static quark $F_Q(T) = -T \ln L_{ren}(T)$. The renormalization procedure of the Polyakov on the lattice introduces a scheme dependence. Therefore, for the comparison of the hadron resonance gas with the lattice data one needs to adjust the parameter Δ in Eq. (4). Fitting the parameter Δ to all available continuum lattice data in the temperature interval $123 \text{ MeV} \leq T \leq 135 \text{ MeV}$ we get $\Delta = 580 \pm 5 \text{ MeV}$ with $\chi^2/d.o.f = 0.49$. The comparison of the lattice data with the hadron resonance gas model is shown in Fig. 4. The solid line and the band correspond to the hadron resonance gas result with all the states discussed above and its uncertainty. The dashed line corresponds to the contribution of the ground states only. The figure shows that the contribution of excited states is significant already for the lowest temperature available in the lattice calculations. The hadron resonance gas model can describe the lattice results on the renormalized Polyakov loop up to temperature 140 MeV, however, clearly fails above that temperature. All the excited states included in the analysis are not sufficient to explain the rapid decrease of the static quark free energy. This result agrees qualitatively with the findings of Ref. [16] if the stout data for $T < 140$ MeV are used

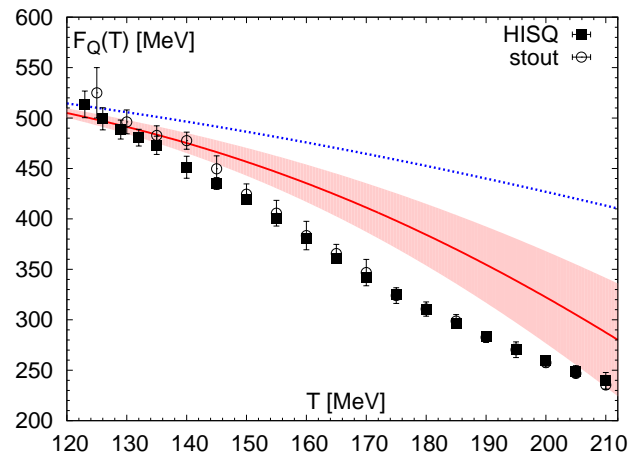


FIG. 4: The free energy of a static quark $F_Q(T)$ calculated on the lattice and compared with the resonance gas model (solid line). The uncertainty of the hadron resonance gas model is indicated by the band. The dotted line is the hadron resonance gas model result with the ground state meson and baryon contribution only.

to normalize the static free energy in their analysis (c.f. Fig. 4 of Ref. [16]). It is also possible that exotic hadron states can explain the discrepancy between the lattice results and hadron resonance gas model for $T > 140$ MeV. Another possibility could be the partial restoration of the chiral symmetry and the corresponding change in the static-light hadron masses, as indicated in a recent lattice study [38].

IV. TEMPERATURE DEPENDENCE OF THE QUARK CONDENSATES

As a byproduct of our study we also calculated the quark condensates $\langle \bar{\psi}\psi \rangle_q$. The quark condensate needs a multiplicative renormalization, and for non-zero quark masses also an additive renormalization. It is easy to see that the leading additive divergence is proportional to the quark mass and is quadratic in the cutoff (inverse lattice spacing). Therefore it was proposed to study the following combination, called the subtracted quark condensate [12]

$$\Delta_{l,s}(T) = \frac{\langle \bar{\psi}\psi \rangle_{l,\tau} - \frac{m_l}{m_s} \langle \bar{\psi}\psi \rangle_{s,\tau}}{\langle \bar{\psi}\psi \rangle_{l,0} - \frac{m_l}{m_s} \langle \bar{\psi}\psi \rangle_{s,0}}. \quad (9)$$

Here $q = l$ and s corresponds to light and strange quarks, while the subscript $x = 0, \tau$ refers to zero and finite temperature expectation values. The expectation values $\langle \bar{\psi}\psi \rangle_{q,x}$ are normalized per single flavor. Sub-leading divergences proportional to the quark mass cubed and the logarithm of the cutoff are expected to be small for the physical values of the light quark masses. We calculated $\Delta_{l,s}$ on $N_\tau = 10$ lattices. Combining this with

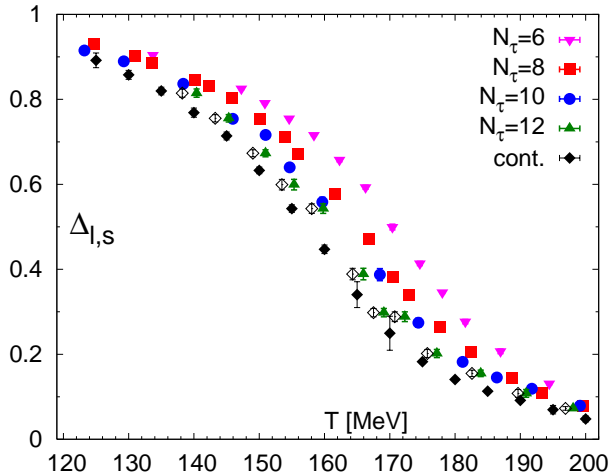


FIG. 5: The subtracted chiral condensate calculated with the HISQ action. The open diamonds correspond to the $N_\tau = 12$ results obtained using the f_K scale [8] (see text).

the published results of the HotQCD collaboration obtained on $N_\tau = 8$ and 12 lattices [8] we performed a continuum extrapolation. First we interpolated the lattice data for each N_τ using a smooth spline and estimated the error of the spline by bootstrap analysis. Next we performed a continuum extrapolation at selected values of temperature separated by 5 MeV within the interval $145 \text{ MeV} \leq T \leq 200 \text{ MeV}$ assuming a $1/N_\tau^2$ behavior. We studied the variation of the extrapolated result with varying the fit range in N_τ . These variations have been included in our final error estimate. For $T < 170 \text{ MeV}$ the $N_\tau = 6$ data have not been included in the analysis as they are incompatible with a $1/N_\tau^2$ behavior. For $T \leq 140 \text{ MeV}$ no $N_\tau = 12$ data are available so the extrapolation had to rely on $N_\tau = 8$ and $N_\tau = 10$ data only. The numerical results for different N_τ as well as the continuum extrapolations are shown in Fig. 5. The continuum extrapolated results are slightly above the continuum results obtained with the stout action [14]. This difference is expected due to the slight difference in the light quark masses used in the two calculations, namely $m_l = m_s/20$ versus $m_l = m_s/27$ in Ref. [14]. In Fig. 5 we also show the $N_\tau = 12$ HISQ data obtained using the lattice spacing determined from the kaon decay constant f_K [8]. These data are systematically above our continuum estimate.

Alternatively, we can get rid of the ultraviolet divergences in the quark condensate by considering the following combination, which is called the renormalized quark condensate [8]

$$\Delta_q^R = d + 2m_s r_1^4 (\langle \bar{\psi}\psi \rangle_{q,\tau} - \langle \bar{\psi}\psi \rangle_{q,0}), \quad q = l, s. \quad (10)$$

Here d is a normalization constant that is related to the light quark condensate in the chiral limit. More precisely, $d = 2m_s r_1^4 \langle \bar{\psi}\psi \rangle_{l,0}(m_l \rightarrow 0)$. With the values of m_s and $\langle \bar{\psi}\psi \rangle_{l,0}(m_l \rightarrow 0)$ from Ref. [39] we get $d = 0.0232244$.

The quantity defined in Eq. (10) is closely related to the renormalized quark condensate $\langle \bar{\psi}\psi \rangle_R$ introduced in Ref. [13]. Using our $N_\tau = 10$ results and the published HotQCD results for $N_\tau = 6, 8$ and 12 we perform a continuum extrapolation for Δ_q^R . As for $\Delta_{l,s}$ we first perform a smooth spline interpolation and estimate the errors of the spline by bootstrap analysis. Then we perform a $1/N_\tau^2$ continuum extrapolation for selected values of the temperature separated by 5 MeV in the interval $145 \text{ MeV} \leq T \leq 200 \text{ MeV}$ based on the interpolation and its errors. We performed extrapolations using subsets of the available N_τ values and the differences in the obtained fit values for Δ_q^R were treated as systematic errors and entered into our final error estimate. For $T \leq 140 \text{ MeV}$ the continuum extrapolations is based on $N_\tau = 8$ and 10 data only.

The lattice QCD results for Δ_l^R and Δ_s^R are shown in Fig. 6 along with the continuum extrapolations. We also show the HISQ $N_\tau = 8$ data obtained using the lattice spacing from f_K in this figure which seem to agree quite well with our continuum result, except for $T > 180 \text{ MeV}$, where they are systematically lower. Our continuum results for Δ_l^R are slightly larger than the continuum results obtained with the stout action [14]. This is again expected to be due to the difference in the light quark masses (see discussion in Ref. [8]). Finally we would like to note the large difference in the temperature dependence of Δ_l^R and Δ_s^R . The decrease of the renormalized strange quark condensate is much more gradual than of the light and Δ_s^R reaches half of its vacuum value only at $T \simeq 200 \text{ MeV}$.

V. CONCLUSIONS

We studied the renormalized Polyakov loop in lattice QCD using the HISQ action and obtained results in the continuum limit for temperatures $120 \text{ MeV} < T < 210 \text{ MeV}$. Results obtained with the HISQ action are in the a^2 scaling regime for $N_\tau \geq 6$. Our continuum results agree well with the earlier findings obtained using the stout action [14]. We studied the question of the physics origin behind the increase in the Polyakov loop, or equivalently, the decrease in the free energy of a static quark F_Q . At sufficiently high temperatures the decrease in F_Q is associated with onset of color screening which also leads to the same decrease in the energy of a static quark at leading order [40]. For temperatures $T < 140 \text{ MeV}$ the decrease in F_Q could be explained in terms of hadron resonance gas model. For larger temperatures the decrease in F_Q appears to be significantly larger and cannot be explained in terms of conventional static-light(strange) hadron states. It remains to be seen whether this rapid decrease is due to the contribution from exotic static-light hadrons or some other mechanism. In the latter case its implication for color screening is not clear, especially in view of recent lattice results on the static energy of $Q\bar{Q}$ pair which do not indicate large significant screen-

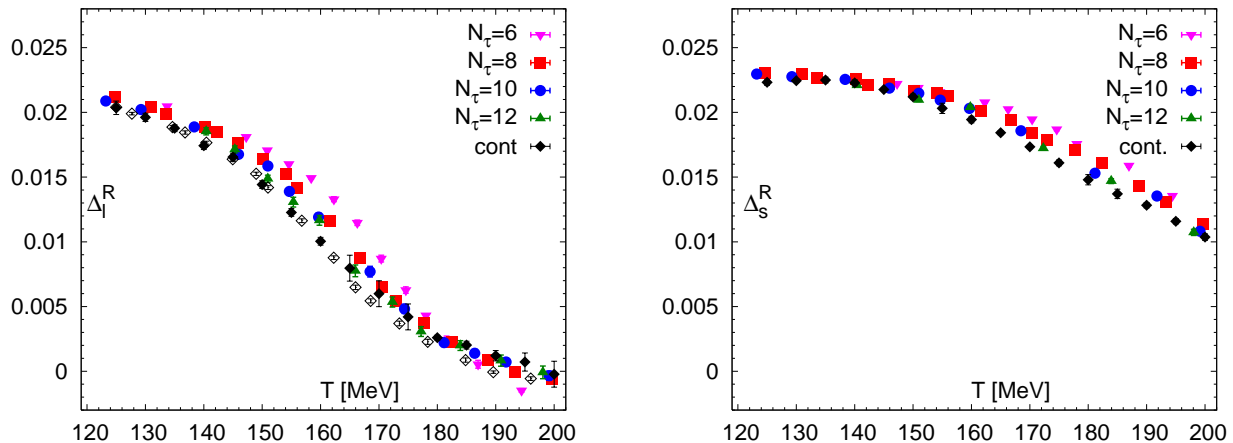


FIG. 6: The light (left) and strange (right) renormalized quark condensate calculated with the HISQ action. Open diamonds correspond to $N_\tau = 8$ HISQ results obtained with the f_K scale [8].

ing effects for $T < 200$ MeV [41, 42]. Currently one of the largest uncertainties in the Polyakov loop calculations within the hadron resonance gas model comes from the excited baryon states. Clearly an improved lattice calculation of static baryon spectrum would be very helpful in this regard. Another open issue is the contribution of exotic static-light hadron states.

We also revisited the calculation of the quark condensate. Combining our $N_\tau = 10$ results with published HotQCD results we performed continuum extrapolations for the subtracted quark condensate as well as for the strange and light renormalized quark condensates. We found that lattice results for these quantities in the transition region follow the expected a^2 scaling if $N_\tau \geq 8$.

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